

IONIZATION IN ATMOSPHERES OF BROWN DWARFS AND EXTRASOLAR PLANETS. I. THE ROLE OF ELECTRON AVALANCHE

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ABSTRACT

Brown dwarf and extrasolar planet atmospheres form clouds which strongly influence the local chemistry and physics. These clouds are globally neutral obeying dust–gas charge equilibrium which is, on short timescales, inconsistent with the observation of stochastic ionization events of the solar system planets. We argue that a significant volume of the clouds in brown dwarfs and extrasolar planets is susceptible to local discharge events. These are electron avalanches triggered by charged dust grains. Such intra-cloud discharges occur on timescales shorter than the time needed to neutralize the dust grains by collisional processes. An ensemble of discharges is likely to produce enough free charges to suggest a partial and stochastic coupling of the atmosphere to a large-scale magnetic field.

Key words: brown dwarfs – plasmas – stars: atmospheres

Online-only material: color figures

1. INTRODUCTION

Brown dwarfs and extrasolar planets have both low luminosity and high surface gravity. Their spectra indicate a complex chemistry due to the low temperatures but high pressures in the atmospheres. This chemical complexity has led to the understanding that condensation processes produce clouds across a large range of effective temperatures (T_{eff} (K)) ranging from late-M dwarfs, the L- and T-dwarfs (Allard et al. 2001; Tsuji 2005; Burrows et al. 2006; Stephens et al. 2009) into the planetary regime (Ackerman & Marley 2001; Fortney et al. 2008; Burningham et al. 2008). Irradiation and star–planet interactions have recently added to the richness of the local chemistry (e.g., Fossati et al. 2010; Spiegel et al. 2009) imposing additional non-equilibrium effects (Vidotto et al. 2010a, 2010b).

This range of spectral types also shows emission at high energies that cannot presently be explained. Quiescent X-ray emission at a constant level of $L_X \approx 10^{-3} L_{\text{bol}}$ and radio emission at a constant level of $L_{\text{radio}} \approx 10^{-7} L_{\text{bol}}$ are present in solar mass stars and persists in stars of lower masses, all the way down to around M7 (Berger et al. 2010). Between M7 and M9 the quiescent level begins to decay, but sporadic, powerful flares are still observed at even later spectral types. A similar slow drop in chromospheric emission is also seen (Reiners & Basri 2008).

In stars like the Sun, this emission is reasonably well understood. These stars generate a magnetic field within their convective interiors. This field rises buoyantly through the interior, to emerge at the stellar surface and extend into the outer atmosphere. The convective motions generate waves along these field lines that transmit some fraction of the convective energy into the outer atmosphere where it is released in reconnection events. The largest of these are observed as X-ray⁵ and radio flares, while the smallest serve to provide the quiescent level of

X-ray emission required to power the corona (Parker 1988). This process, however, relies on a coupling between the convective fluid motions and the magnetic field. Without this coupling, energy cannot be stored in the magnetic field and hence cannot be released in the outer atmosphere to generate coronal X-ray emission. As demonstrated by Mohanty et al. (2002), however, stellar objects between M5 and L6 are too cool for this coupling to be effective. Thermal ionization processes are simply not sufficient to provide a high enough ionization fraction. If these non-binary low-mass objects are so cool, then how do we explain the observed X-ray emission? The presence of this emission indicates an ionized atmosphere, but the cause of this ionization is unknown.

The key to this puzzle may lie in the dust clouds that begin to form in low-mass stars at around the same effective temperature range where thermal ionization processes die away. Within the solar system, cloud-covered planets are observed to produce various kinds of discharge events (e.g., Yair 2008). On Earth, dust storms and volcanoes are examples for strong intra-cloud discharging of dusty gases. We argue in this paper that such discharge events are to be expected in the dusty gases of extrasolar atmospheres, in analogy to their solar system counterparts. If they could raise the ionization fraction by a sufficient amount, over a large enough volume, then they may be able to explain the presence of sustained quiescent X-ray emission in objects as cool as M9 and the presence of large flares in even lower mass objects.

There is, however, an immediate problem with this suggestion, which is that classical charge equilibrium arguments point to a rapid neutralization of dust particles. This would imply that these cool, dusty atmospheres are neutral, at least on long timescales. Observations of solar system planets and laboratory discharge events, however, suggest that on *short* timescales, discharge events should be expected. We propose that some rapid process, such as the electron avalanche believed to act in lightning bolts, may operate. Assuming that dust grains can be charged for long enough for avalanches to occur, they may be

⁵ The X-ray luminosity results from thermal gyrosynchrotron radiation resulting from thermally produced electrons only.

capable of providing local and intermittent ionization. Depending on the volume of the atmosphere that is susceptible to this process, and the frequency with which it occurs, this may be capable of explaining a low level of magnetic field coupling and hence quiescent X-ray emission, or only intermittent coupling, leading to occasional flaring.

In Section 2, we first briefly summarize cloud properties of brown dwarfs and extrasolar planets and we investigate the geometrical extension of clouds depending on the fundamental parameters T_{eff} and $\log(g)$. By assuming that the dust grains, which compose the clouds, are charged, we discuss their effect on the local charge balance in Section 3. In Section 4, we demonstrate that dust-initiated electron avalanches are a strong candidate to temporally increase the local degree of gas phase ionization in the atmospheres of brown dwarfs and extrasolar planets.

2. DUST IN BROWN DWARF AND EXOPLANETARY ATMOSPHERES

We analyze results from the dust-cloud model developed by Woitke & Helling (2003, 2004), Helling & Woitke (2006), and Helling et al. (2008c, 2008d) describing consistently the formation of a stationary cloud by homogeneous nucleation and dirty growth/evaporation, including gravitational settling, element depletion, and convective element replenishment. In the following, we utilize DRIFT-PHOENIX atmosphere models (Dehn 2007; Helling et al. 2008a, 2008b; Witte et al. 2009) in which our detailed kinetic model of dust-cloud formation is coupled with a radiative transfer code (Hauschildt & Baron 1999, Baron et al. 2003). This allows for a consistent solution of the model atmosphere problem and the dust cloud model from which we derive the geometrical extension of the cloud. Based on DRIFT-PHOENIX model atmospheres, we have shown that clouds form in atmospheres of brown dwarfs and extrasolar planets, and that they are composed of chemically heterogeneous grains of various sizes. The local grain size distribution is dominated by small grains at the cloud top and by large grains at the cloud base. These dust grains gravitationally settle and change their chemical composition and their sizes during this journey through the atmospheric temperature gradient until they evaporate. The cloud's material composition, however, is similar amongst the brown dwarfs and giant gas planets (Helling et al. 2008c, 2008d) except if the element abundances are very low ($[M/H] < -4.0$; Witte et al. 2009). The geometrical cloud extension can change considerably with $\log(g)$.

The geometrical extension of the cloud is determined by the maximum distance over which grains can fall before they evaporate. The cloud extension⁶ is taken as the geometrical distance between the first nucleation maximum (cloud top) and the point at which the dust has evaporated at high temperatures (cloud base), hence $\Delta H_{\text{cloud}} = (r_{\text{top}} - r_{\text{base}}) \cdot R_*$ where fractional distances r are scaled to the radius R_* . Figure 1 (top) shows that the dependence of the cloud extension on the brown dwarf's T_{eff} is comparably weak with a cloud extension of $H_{\text{cloud}} \approx 0.00036 \dots 0.00041 R_*$. As an example, a Jupiter-sized brown dwarf ($R_* = R_J = 7.1492 \times 10^9 \text{ cm}$; equatorial Jupiter radius) with a surface gravity of $\log(g) = 5.0$ would

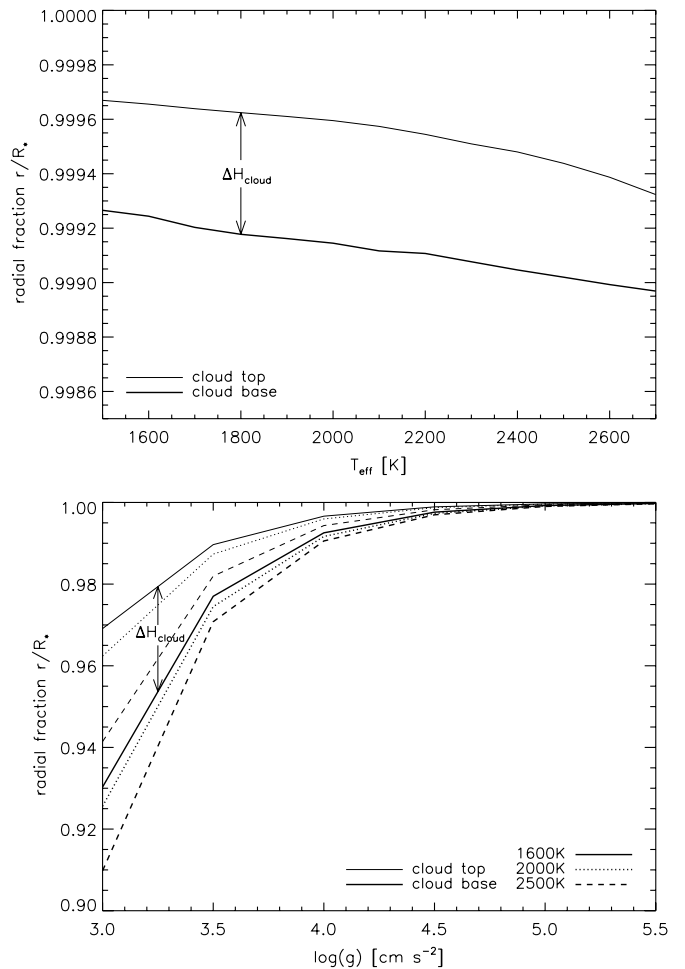


Figure 1. Cloud extension $\Delta H_{\text{cloud}} = (r_{\text{top}} - r_{\text{base}}) \times R_*$ as a function of T_{eff} (top, $\log(g) = 5.0$) and $\log(g)$ (bottom) from DRIFT-PHOENIX model atmospheres. The cloud's top ($@r_{\text{top}}(R_*)$, thin lines) is defined at the first nucleation maximum, the cloud base ($@r_{\text{base}}(R_*)$, thick lines) is defined at the location where all dust is evaporated (Figure 2 in Witte et al. 2009).

form clouds that spanned 27.5 km, i.e., $0.000385 R_*$ (Figure 1, top). Measuring cloud extension from observations is, however, not straightforward as observations only access the (frequency-dependent) optically thin part of the cloud while the geometrical extension of the cloud layer is often much larger (e.g., Banfield et al. 1998, Matcheva et al. 2005 for Jovian clouds; Pont et al. 2008 and Sing et al. 2009 for extrasolar clouds).

The extension of the cloud changes much more significantly, however, with $\log(g)$ (Figure 1, bottom). It increases considerably for young brown dwarfs and gas giant planets as they have a much lower surface gravity of $\log(g) \approx 2.5\text{--}4.0$ compared to old brown dwarfs with $\log(g) > 4.0$. This reflects the increasing pressure scale height with decreasing gravity as $\Delta H_p \sim 1/g$. The cloud extension increases from $\Delta H_{\text{cloud}} = 0.004 \dots 0.005 R_*$ for $\log(g) = 4.0$ to $\Delta H_{\text{cloud}} = 0.03 \dots 0.04 R_*$ for $\log(g) = 3.0$ by almost a factor 10 (Figure 1). Table 1 shows examples for brown dwarfs and WASP planets by assuming that ΔH_{cloud} varies only slowly with T_{eff} . Depending on the object's radius and surface gravity, the cloud extension varies between some 10 km and 5000 km.

3. CHARGE BALANCE IN DUSTY ATMOSPHERES

We therefore expect that brown dwarfs and extrasolar planets will form dust clouds whose geometrical extent depends mainly

⁶ This definition is different to Woitke & Helling (2004). The geometrical thickness of the cloud layer was defined in Woitke & Helling (2004) as the degree of condensation of Ti $f_{\text{cond}}^{\text{Ti}} = \epsilon_{\text{Ti}}^{\text{dust}} / \epsilon_{\text{Ti}}^0 > 1/e$ having decreased to $1/e$ at the cloud deck and the cloud base. $\epsilon_{\text{Ti}}^{\text{dust}}$ is the element abundance contained in the solid phase and ϵ_{Ti}^0 the undepleted element abundance.

Table 1

Cloud Extension, ΔH_{cloud} , for Brown Dwarfs and WASP-like Giant Gas Planets^a as Derived from the DRIFT-PHOENIX Atmosphere Simulation Results in Figures 1

Object	Reference	T_{eff} [K]	$\log(g)$	R_* [R_J]	ΔH_{cloud} [R_*]	ΔH_{cloud} [km]
WASP 12b	Hebb et al. (2009)	2516	2.9	1.79	0.030	3820
WASP 15b	West et al. (2009)	1652	2.8	1.43	0.040	3830
WASP 10b	Christian et al. (2009)	1119	3.6	1.28	0.011	1000
WASP 14b	Joshi et al. (2009)	1866	4.0	1.28	0.005	410
2MASS J05352184-0546085 (binary system)						
1	Stassun et al. (2007)	2700	3.6	6.52	0.012	5620
2	Stassun et al. (2007)	2800	3.5	4.67	0.011	3710

Notes. All T_{eff} for the WASP planets are taken as $A = 0$ (A —albedo; see references in table).

^a ($R_J = 7.1492 \times 10^9$ cm—Equatorial Jupiter Radius; $R_\odot = 6.9598 \times 10^{10}$ cm—Solar Radius).

on the surface gravity. Although the presence of these dust clouds undoubtedly influences the local chemistry, it remains an open question whether they can significantly influence the large-scale dynamics. The observation of X-ray flares and coherent radio emission from brown dwarfs (Berger et al. 2010) suggests that they must possess a magnetic field. The presence of a global magnetic field opens up the possibility of coupling between this field and the gas in which it is embedded. In this case, by analogy with the Sun and solar-type stars, we would expect that the magnetic field may become twisted and tangled by the convective motions. This process stores magnetic energy throughout the field and it is the release of this energy by many reconnection events that is believed to power the persistent X-ray emission from the coronae of solar-like stars. If, as on the Sun, brown dwarf flares are magnetically powered, then there must have been at least a short-term, coupling between the magnetic field and the plasma.

The level of this field coupling is typically measured by the value of the magnetic Reynolds number R_m which is the ratio of the advective and diffusive contributions to the temporal evolution of the magnetic field. A magnetic field may be considered to be effectively coupled to the plasma if diffusion is negligible compared to advection and hence $R_m > 1$. This requires, however, that there is a significant level of ionization of the plasma, since the magnetic Reynolds number is proportional to the atmospheric ionization fraction $f_e = p_e^{\text{tot}}/p_{\text{gas}}$, such that

$$R_m = u l \eta_d^{-1} \quad (1)$$

$$= u l \cdot \frac{4\pi q^2}{m_e c^2} \frac{1}{\langle \sigma v \rangle_{\text{en}}} \cdot f_e, \quad (2)$$

where η_d is the magnetic diffusivity, q is the electric charge, c is the speed of light, m_e is the mass of the free electron, and $\langle \sigma v \rangle_{\text{en}} \approx 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ is the collisional cross section (velocity averaged momentum transfer cross section; Pinto & Galli 2008). We choose $u = 10^4 \text{ cm s}^{-1}$ as representative, large-scale velocity value (Figure 9 in Freytag et al. 2010) and $l = 10^5 \text{ cm}$.

The magnetic Reynolds number and hence the degree of atmospheric coupling will therefore vary with depth in the atmosphere as the ionization fraction varies. Figure 2 demonstrates this variation using the local gas pressure as a measure of atmospheric depth, while Figure 3 describes its variation with

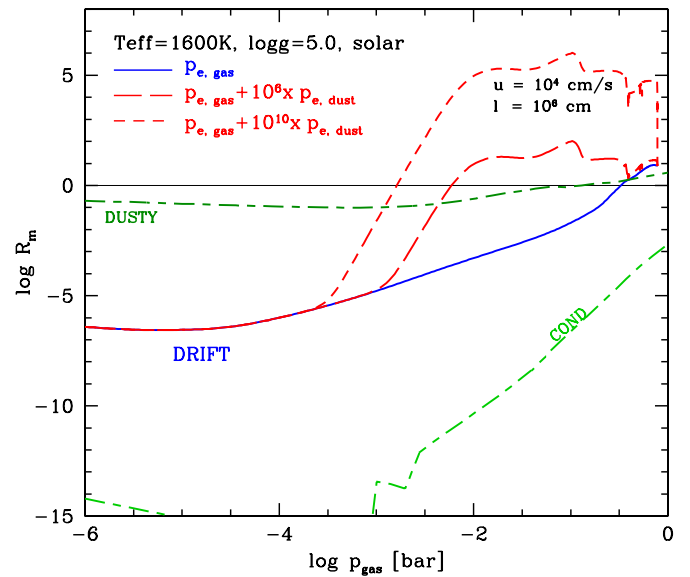


Figure 2. Magnetic Reynolds number, $R_m = u l \eta_d^{-1}$, for a DRIFT-PHOENIX model atmosphere (blue) and a comparison with DUSTY-PHOENIX (dark green) and COND-PHOENIX (light green) results for thermal gas ionization only. Magnetic coupling of the gas to a magnetic field is expected if $R_m > 1$, hence above the black horizontal $R_m = 1$ line. Overplotted are the cases with a charge production that has been artificially increased by a factor of 10^6 (long dashed line) and 10^{10} (short dashed line) inside the cloud. This demonstrates that magnetic coupling can be expected in limited parts of the dusty atmosphere if such a high number of charges can be produced.

(A color version of this figure is available in the online journal.)

the cloud's radial fraction [r/R_*]. Figure 2 contains results of several different atmospheric codes. The DRIFT-PHOENIX results are compared to results for the DUSTY-PHOENIX (green dashed line, Figure 2) and the COND-PHOENIX (brown dashed lines, Figure 2) model atmospheres.⁷ DUSTY-PHOENIX produces a considerably higher R_m due to thermal gas ionization owing to an overall hotter temperature in the atmosphere compared to COND-PHOENIX and DRIFT-PHOENIX.

Only the very inner parts of the atmosphere reach $R_m > 1$ by thermal gas ionization in the DUSTY- and DRIFT-PHOENIX model atmospheres. Thermal gas ionization is, hence, not sufficient to couple the gas inside and above the dust cloud to the magnetic field as already shown by Gelino et al. (2002) and Mohanty et al. (2002). A significant increase in the electron number density would be required to ensure that $R_m > 1$. In order to illustrate this point, we show in Figure 2 that an increase of the electron number density by a factor 10^6 per cloud altitude would be needed to ensure $R_m > 1$ (long dashed red line, Figure 2). This translates into $>50\%$ of the cloud (long dashed red line in Figure 3) being coupled to any magnetic field present. This would be the inner ~ 13 km of a cloud of a Jupiter-sized brown dwarf (Section 2). Note that the atmospheric volume concerned increases with decreasing surface gravity of the object, and hence, for young brown dwarfs or giant gas planets (Section 2).

It is clear, therefore, that in order to maintain a state whereby most of the cloud is ionized sufficiently to ensure an effective coupling to any magnetic field present, we require a significant and sustained enhancement of the electron number density. The magnitude of this enhancement can be illustrated quite simply by considering charge balance in the cloud. The electron density,

⁷ DUSTY-PHOENIX and COND-PHOENIX are older versions of the PHOENIX model atmosphere results where the existence of dust was assumed rather than its formation calculated.

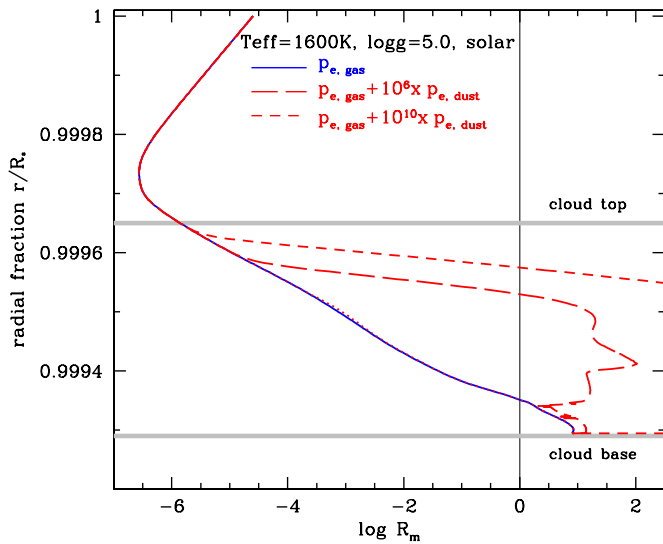


Figure 3. Magnetic Reynolds number, $R_m = u l \eta_d^{-1}$ in relation to the cloud height for the DRIFT-PHOENIX model atmosphere only. “Cloud top” and “cloud base” are defined as in Figure 1.

(A color version of this figure is available in the online journal.)

n_e , changes due to electron production processes ($I = I_{\text{gas}} + I_{\text{dust}}$) and electron recombination processes ($R = R_{\text{gas}} + R_{\text{dust}}$), such that, in equilibrium,

$$\frac{dn_e}{dt} = I_{\text{gas}} + I_{\text{dust}} - R_{\text{gas}} - R_{\text{dust}} = 0. \quad (3)$$

We neglect the thermal gas-phase processes, I_{gas} and R_{gas} , as we (also Gelino et al. 2002; Mohanty et al. 2002) have demonstrated that thermal ionization of the gas phase is negligible in brown dwarf atmospheres. If the electron production and electron neutralization are due to collisional processes with the dust grains only, then

$$I_{\text{dust}} \sim N n_d^2 \pi a^2 v_{\text{rel}}, \quad (4)$$

$$R_{\text{dust}} \sim n_e n_d \pi a^2 c_e, \quad (5)$$

with n_d being the dust number density, N the number of charges produced by a collision, a the dust grain radius, v_{rel} a relative velocity, and c_e the electron thermal velocity. Thus, we simply have

$$\frac{I_{\text{dust}}}{R_{\text{dust}}} \sim N \frac{n_d}{n_e} \frac{v_{\text{rel}}}{c_e}. \quad (6)$$

The presence of dust can only significantly increase the electron density if $I_{\text{dust}} \gg R_{\text{dust}}$ and, hence $N n_d \gg n_e$. Since the number density of dust grains is so much less than that of electrons, we require that the number of charges N produced by collisions must increase dramatically. We estimate that $I_{\text{dust}}/R_{\text{dust}} \sim 7 \times 10^{-13} N$, hence we require $N > 1.4 \times 10^{12}$ in the low-pressure part at $p_{\text{gas}} \sim 10^{-5}$ bar of the cloud.⁸ Conditions would be more favorable at higher pressures as fewer free charges would be needed: at a pressure of 10^{-2} bar, $I_{\text{dust}}/R_{\text{dust}} \sim 8.5 \times 10^{-11} N$, and hence only $N > 1.2 \times 10^{10}$

is required.⁹ These numbers are, however, sufficiently large that it is unlikely that the simple collisional processes we have considered will be sufficient to produce an equilibrium state with $R_m > 1$. We therefore expect that even in the presence of dust clouds, the atmospheres of brown dwarfs should be globally neutral. This does not, however, preclude short-term departures from equilibrium which might (as in the solar system) lead to transient ionization events.

Concluding this section, we have demonstrated that a considerable number of additional charges is needed to allow $R_m > 1$, or equivalently, to provide a minimum degree of ionization of $f_e > 10^{-7}$. These charges need to be produced (or separated) on a timescale shorter than a classical collisional recombination timescale of grains in order to keep the atmosphere globally neutral over a long timescale.

4. ELECTRON AVALANCHE IN CLOUDS

We have argued that the consideration of thermal- and dust-collisional processes alone suggests a globally neutral atmosphere, but that processes acting on shorter timescales can cause a violation of strict charge equilibrium locally. This would be consistent with intermittent X-ray flares on brown dwarfs, where a rapid release of energy produces intense X-ray emission for a short time, followed by long periods of quiescence. We suggest electron avalanche initiated by charged dust grains as one candidate for the fast production of large amounts of free charges, and hence as source for a locally increased degree of gas ionization in the atmospheres of brown dwarfs and extrasolar planets.

We assume that dust grains are charged, as discharge events are observable in a variety of environments (terrestrial thunder clouds, dust devils, volcano plumes) and are expected to occur in others (protoplanetary disks; Desch & Cuzzi 2000). These dust grains form and have relative velocities, e.g., by gravitationally settling and turbulence which determines the cloud’s geometrical extension in an atmosphere (Woitke & Helling 2003; Helling & Woitke 2006).

Experiments have shown that a $100 \mu\text{m}$ particle can carry 10^5 elementary charges (Sickafoose et al. 2000). If we consider grains that are three orders of magnitude smaller, their charge load will be smaller by about the same order of magnitude. Helling et al. (2008c, 2008d) have shown that the cloud’s grain size distribution per altitude can be very broad in particular in low-gravity objects ($\log(g)=3.0$) containing of order 10^4 particles as large as $10 \mu\text{m}$. If these large particles would only release 1/100 of their accumulate 10^4 charges into the gas phase before electron recombination, $> 50\%$ of the cloud would achieve $R_m > 1$ (see Figure 3). These charges may, however, neutralize by collisional recombination unless an avalanche instability like for instance in streamers can develop on a shorter timescale (see Section 4.1).

If enough charges remain on the grain surface (or none are released into the gas phase), and the grains move with a relative velocity, a strong electric field can be established that initiates a small-scale discharge between the grains. A current forms that tries to establish charge balance. Free thermal electrons gain enough energy when moving through the grain’s small-scale

⁸ We have adopted values for the low-pressure part of a cloud at $p_{\text{gas}} \sim 10^{-5}$ bar where $T \sim 1000$ K, $n_d \sim 10^{-10} \text{ cm}^{-3}$ (Helling et al. 2008b), $v_{\text{rel}}^{\text{drift}} \sim 10^4 \text{ cm s}^{-1}$ (Witte et al. 2009), $n_e \sim 0.076 \text{ cm}^{-3}$ for $p_e \sim 10^{-14} \text{ dyn cm}^{-2}$. The electron thermal velocity is $c_e = \sqrt{2kT/m_e} \sim 1.7 \times 10^7 \text{ cm s}^{-1}$.

⁹ We have adopted values for a part of the cloud with a higher pressure of $p_{\text{gas}} \sim 10^{-2}$ bar where $T \sim 1150$ K, $n_d \sim 10 \text{ cm}^{-3}$ (Helling et al. 2008b), $v_{\text{rel}}^{\text{drift}} \sim 10^2 \text{ cm s}^{-1}$ (Witte et al. 2009), $n_e \sim 6.3 \times 10^5 \text{ cm}^{-3}$ for $p_e \sim 10^{-8} \text{ dyn cm}^{-2}$. The electron thermal velocity is $c_e = \sqrt{2kT/m_e} \sim 1.9 \times 10^7 \text{ cm s}^{-1}$.

electric field to be able to ionize the gas between the grains. Eventually the field disappears as the grains move further apart. What remains is a partly ionized ambient atmosphere while the charged grains escape due to gravitational settling. We can estimate the electric field developed by considering a spherical grain of mean size $a = 0.5 \mu\text{m}$ carrying $q = 3 \times 10^3 e$ charges (Desch & Cuzzi 2000). This gives

$$E = \frac{q}{4\pi\epsilon_0 a^2} = 20 \text{ MV m}^{-1}, \quad (7)$$

where ϵ_0 is the electrostatic field constant, and e is the elementary charge. Dowds et al. (2003) demonstrate the effectiveness of a succession of these avalanches (known as a *streamer*) in ionizing the nitrogen gas between two capacitor plates for a field strength of only 5 MV m^{-1} . Li et al. (2007, 2008) support this finding for an electric field strength of 10 MV m^{-1} from their study based on different numerical methods. Hence, the field strength between charged grains is sufficient to produce streamers that enhance the local degree of gas ionization inside the dust cloud. The electric field will be stronger if the grain's shape depart from spherical symmetry (Stark et al. 2006).

The streamers that form are a growing ionization front that propagates into non-ionized matter. They are present in lightning ladders and they can emerge from ionization avalanches in weakly ionized plasmas in free space. Such field breakdowns are stochastic and non-linear processes that produce an exponentially increasing number of charges. Streamers are self-sustaining (hence an instability), and each streamer is ignited by the large number ($\sim 10^6$) of free charges produced by the avalanche of the accelerated electron from one gas-phase electron-ion pair. Between 10^{13} and 10^{14} cm^{-3} free charges form during the consecutive avalanches in the streamer (Dowds et al. 2003; Li et al. 2007). One streamer alone is therefore capable of satisfying $I_{\text{dust}} \gg R_{\text{dust}}$ locally, and hence causing departure from local charge equilibrium.

Such local ionization events are only likely to be capable of explaining the observations of brown dwarf flares and radio emission if they occur over a sufficiently large volume of the atmosphere. The cloud grains, however, are confined to a certain volume of the atmosphere by thermodynamic constraints. This volume increases with decreasing surface gravity as we have shown in Section 2. The cloud height would be the maximum size that a streamer leading to a lightning bolt could achieve in the case of intra-cloud lightning. In this volume, the simultaneous occurrence of discharge in streamers will occur, and the gas in the cloud could then locally couple to the magnetic field for a short time appearing as, e.g., stochastic flares. Over a recombination time, we expect that these excess charges will recombine onto dust grains.

4.1. Neutralization Versus Avalanche Timescales

We have argued that dust grains populate brown dwarf and extrasolar planet atmosphere over an extension that varies mainly with gravity. We have further argued that non-linear processes are needed to produce discharge processes such as those in solar system planets, and we have suggested exponential electron avalanche as an attractive possibility. It remains to be shown if the grains could be neutralized by gas-dust collisions quickly enough to prohibit the built-up of the streamer-avalanche mechanism that leads to the appearance of lightning bolts.

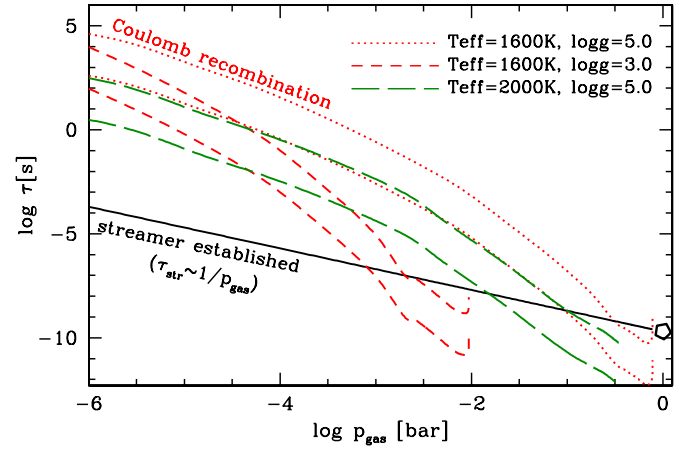


Figure 4. Timescale of grain neutralization by freely impinging electrons $\tau_{\text{recom}}^{\text{cgs}}$ (red and green dashed and dotted lines) compared to the time required to establish a streamer τ_{str} (black solid line). The neutralization timescale τ_{str} is shown for three different DRIFT-PHOENIX atmosphere models (hot/cold and high/low $\log(g)$), which are each evaluated for two cases: charge load of small grains ($q = 10e$, upper line) and larger grains ($q = 10^2e$, lower line). The black symbol is the numerical data from Dowds et al. (2003) extrapolated such that $\tau_{\text{str}} \sim 1/p_{\text{gas}}$ (see footnote 10).

(A color version of this figure is available in the online journal.)

Dowds et al. (2003) carried out numerical experiments where the electron avalanche process and the development of streamers were studied between two 0.1 cm size capacitor plates with a plate distance of $5 \mu\text{m}$. The capacitor was filled with nitrogen gas of a typical terrestrial atmospheric pressure of 1 bar . They show that a streamer is fully developed after about $\tau_{\text{str}} = 0.2 \text{ ns}$ ($= 2 \times 10^{-10} \text{ s}$; black symbol, Figure 4), a timescale confirmed by comparable works of Li et al. (2008) and by three-dimensional simulations of Li et al. (2009). Following Ebert et al. (2010), we scale τ_{str} with the local gas pressure as $\tau_{\text{str}} \sim 1/p_{\text{gas}}$ (solid black line, Figure 4¹⁰).

To estimate the grain charge neutralization timescale, we adopt the neutralization rate given by Desch & Cuzzi (2000, Equation (24)), which assumes that electrons can freely impinge on the positively charged grain's surface if the Coulomb energy of the grain is larger than the thermal kinetic energy of the electrons. This timescale provides an estimate for efficient neutralization as electrons have a higher mobility than the much heavier ions. From their formula, one derives the neutralization timescale for a grain of size a (Equation (25) in Desch & Cuzzi 2000) in cgs units¹¹ applying the mean grain size, $\langle a \rangle$, from our DRIFT-PHOENIX model

$$\tau_{\text{recom}}^{\text{cgs}} = \frac{1}{q^2} \frac{kT}{n_e c_e \pi \langle a \rangle}, \quad (8)$$

¹⁰ The timescale to establish a streamer can also be defined as

$$\tau_{\text{str}} = \frac{N(x(t))}{\frac{dN(x(t))}{dt}},$$

with $N(x(t)) = N_0 \exp(\frac{x(t)}{\lambda_e})$ the exponential growth of charges in a streamer (e.g., Braithwaite 2000). With N_0 the initial values of number of charges dropping out of the equation, by assuming a stationary electron velocity ($dx(t)/dt = \text{constant}$) through the capacitor, and with the electron's mean free path $\lambda_e \sim 1/p_{\text{gas}}$, it follows that $\tau_{\text{str}} \sim 1/p_{\text{gas}}$.

¹¹ The neutralization timescale is in SI units ($e = 1.602 \times 10^{-19} \text{ C}$),

$$\tau_{\text{recom}}^{\text{SI}} = \frac{4\pi\epsilon_0}{q^2} \frac{kT}{n_e c_e \pi \langle a \rangle}.$$

where n_e is the gas-phase electron density, $c_e = \sqrt{2kT/m_e}$ is the electron thermal velocity, and m_e is the electron mass. We show two limiting cases for the grain charge q according to Fortov et al. (2001) where small grains carry of the order of $q = 10e$ (each upper line) and large grains $q = 10^2e$ (each lower line). The elementary charge is in units of $e = 4.803 \times 10^{-10}$ statC. We also include the recombination timescales for a hotter ($T_{\text{eff}} = 2000$ K, $\log(g) = 5.0$; green long dashed) and a lower-gravity atmosphere model ($T_{\text{eff}} = 1600$ K, $\log(g) = 3.0$; red short dashed) for comparison. The timescale for dust grain neutralization by impinging electrons is longer than the time needed to establish a streamer (solid black line) throughout a significant fraction of the cloud in all the model atmospheres considered (Figure 4). Only the largest particles at the cloud base would neutralize too quickly for the streamer mechanisms to kick in efficiently if the neutralization process proceeds without collisions as assumed in Equation (8). We note that this is also the part of the cloud where the largest particles accumulate and quickly evaporate inside a narrow cloud layer. These grains are almost pure metal as they are made of Fe[s] with small inclusions of TiO₂[s] and Al₂O₃[s] followed by a thin cloud region with almost homogeneous Al₂O₃[s] grains ([s]—solid).

5. CONCLUSIONS

Brown dwarf and extrasolar planet atmospheres form clouds which strongly influence the local chemistry and physics. These clouds need to form from the gas phase as brown dwarfs and most of the planets do not have a crust from which seed particles can be swept up. These clouds are globally neutral obeying dust-gas charge equilibrium. On short timescales, however, stochastic ionization events may occur as observed in the solar system planets. We have argued that a large part of the clouds in brown dwarfs and extrasolar planets is susceptible to local discharge events which are triggered by charged dust grains. Such discharges occur on timescales shorter than the time required to neutralize the dust grains, and their superposition might produce enough free charges to suggest a partial and stochastic coupling of the atmosphere to a large-scale magnetic field. Discharge processes in brown dwarf and exoplanetary atmospheres cannot connect to a crust as on terrestrial planets, hence, they will experience intra-cloud discharges comparable to volcano plumes and dust devils.

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